

# Ionization structure and Fe $K\alpha$ energy for irradiated accretion disks

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## ABSTRACT

We study the radial ionization structure at the surface of an X-ray illuminated accretion disk. We plot the expected iron  $K\alpha$  line energy as a function of the Eddington ratio and of the distance of the emitting matter from the central source, for a non-rotating and a maximally-rotating black hole. We compare the predicted disk line energies with those measured in an archival sample of active galactic nuclei observed with *Chandra*, *XMM-Newton* and *Suzaku*, and discuss whether the line energies are consistent with the radial distances inferred from reverberation studies. We also suggest using rapidly-variable iron  $K\alpha$  lines to estimate the viscosity parameter of an accretion disk. There is a forbidden region in the line energy versus Eddington ratio plane, at low Eddington ratios, where an accretion disk cannot produce highly-ionized iron  $K\alpha$  lines. If such emission is observed in low-Eddington-ratio sources, it is either coming from a highly-ionized outflow, or is a blue-shifted component from fast-moving neutral matter.

**Key words:** accretion, accretion discs — X-rays: galaxies — galaxies: active — quasars: emission lines

## 1 INTRODUCTION

Recent high-resolution spectral studies by *Chandra*, *XMM-Newton* and *Suzaku* have revealed that emission lines at 6.7 or 6.9 keV (probably emitted by highly ionized iron) are common features in the X-ray spectra of active galactic nuclei (AGNs, e.g., Pounds et al. 2003; Reeves et al. 2004; Yaqoob & Padmanabhan 2004; Bianchi et al. 2009; Shu et al. 2010; Patrick et al. 2010). The  $K\alpha$  emission lines produced by ionized iron in optically thin, photoionized material in AGNs have been studied by Bianchi & Matt (2002). Their results may require an iron overabundance by a factor of a few to account for the observed line strength.

The energy and ionization balance at the surface of an accretion disk can change due to the X-ray illumination, and this affects the line emission. Thus, it is important to determine the radial ionization structure of X-ray photoionized accretion disks, in order to study the reflected spectra and the associated iron  $K\alpha$  emission. The energy of the iron  $K\alpha$  line generally increases as iron becomes more stripped, from 6.4 keV for Fe I to 6.97 keV for Fe XXVI (Kaspi et al. 2002; Paerels & Kahn 2003). This provides a diagnostic of

the accretion disk structure: we can compare the calculated photoionization structure of the disk with the observed energy of the iron  $K\alpha$  line, assuming that the line was emitted from the disk.

In this letter, we calculate the radial ionization structure of an X-ray illuminated AGN accretion disk as a function of Eddington ratio,  $\lambda_{\text{Edd}} \equiv L_{\text{bol}}/L_{\text{Edd}}$ , where  $L_{\text{bol}}$  is the bolometric luminosity and  $L_{\text{Edd}}$  is the Eddington luminosity. We then compare the predicted range of ionization parameters and iron  $K\alpha$  line energies with a sample of recent line observations. We plot the predicted and observed line energies  $E_\alpha$  as a function of  $\lambda_{\text{Edd}}$ . This gives us clues on the origin of the iron  $K\alpha$  lines. Throughout this Letter, we assume standard cosmological parameters  $h_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $\Omega_m = 0.27$ , and  $\Omega_\Lambda = 0.73$ .

## 2 METHODS AND RESULTS

X-ray reflection from the surface of cold matter around compact accreting objects has been studied by many authors (Basko et al. 1974; Guilbert & Rees 1988; Lightman & White 1988; White et al. 1988; George & Fabian 1991; Matt et al. 1991; Done et al. 1992; Ross & Fabian 1993; Matt et al. 1993; Czerny & Życki

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1994; Krolik et al. 1994; Magdziarz & Zdziarski 1995; Ross et al. 1996; Reynolds & Begelman 1997; Blackman 1999; Nayakshin et al. 2000; Young & Reynolds 2000; Nayakshin & Kallman 2001; Ballantyne et al. 2002; Miniutti & Fabian 2004; etc). Following those studies, we assume an idealized lamppost geometry for the X-ray illumination of the reprocessing matter: all the X-rays are emitted isotropically by a point source located on the symmetry axis above a standard accretion disc (Shakura & Sunyaev 1973), at a certain height  $h$ . Ignoring the effects of light bending in the vicinity of the black hole (BH), the ionization parameter is

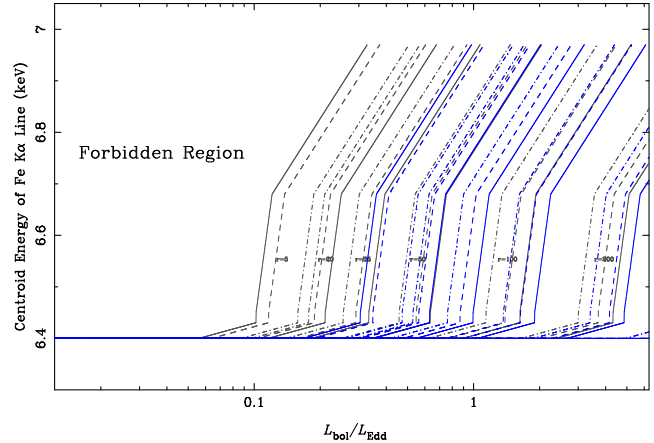
$$\xi = 8.97 \times \left( \frac{\lambda_{\text{Edd}}^3 \eta_{\text{x}} \alpha}{\eta^2} \right) f^2(r) r^{-3/2} \frac{h}{(r^2 + h^2)^{3/2}} \quad (1)$$

(Matt et al. 1993; Ross & Fabian 1993), where  $r$  is the radial coordinate on the disk,  $f(r) = 1 - \sqrt{6/r}$ ,  $\eta$  is the total radiative efficiency,  $\eta_{\text{x}}$  is the X-ray fraction ( $L_{\text{x}} \equiv \eta_{\text{x}} \lambda_{\text{Edd}} L_{\text{Edd}}$ ), and  $\alpha$  is the viscosity parameter. In Eq.(1),  $h$  and  $r$  are in units of  $r_{\text{g}} \equiv GM_{\text{BH}}/c^2$ . The efficiency  $\eta = 0.06$  for a Schwarzschild BH and  $\eta = 0.31$  for a maximally spinning astrophysical BH (Thorne 1974). Here we assume a standard value of viscosity parameter of  $\alpha \sim 0.1$ , although a large range of values has been used in previous studies, from  $\alpha \sim 0.01$  (Miller & Stone 2000; Starling et al. 2004) to  $\alpha \sim 0.3$  (Esin et al. 1997).

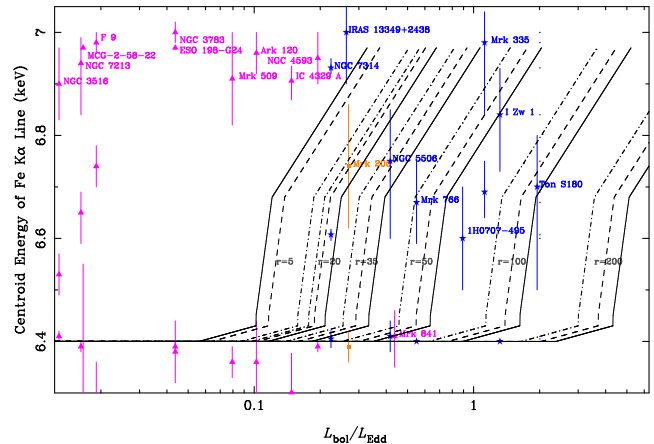
We took the values of the iron K $\alpha$  line energy emitted by an X-ray illuminated disk as a function of  $\xi$  from the calculations of Matt et al. (1993, Fig 1b). Note that the relation between  $E_{\alpha}$  and  $\xi$  is almost independent of the incident angle of the illuminating flux; here we assume that  $E_{\alpha}$  is only a function of the iron ionization state. Using Eq.(1), we calculated  $E_{\alpha}$  as a function of  $\lambda_{\text{Edd}}$  for different values of  $h$  and  $r$  (Figure 1). Plotted as black lines are the results for a Schwarzschild BH; the blue lines are the results for a maximally-spinning Kerr BH. We repeated the calculation for six values of  $r$  between  $5r_{\text{g}}$  and  $200r_{\text{g}}$  in the Schwarzschild case, and the same six values of  $r$  in the Kerr case. The radial values are plotted as labels in Figure 1, next to the Schwarzschild curves. For each value of  $r$ , we performed our calculation for three values of  $h = 5r_{\text{g}}$ ,  $8r_{\text{g}}$ , and  $15r_{\text{g}}$ . The curves corresponding to those three values of  $h$  are plotted as solid, dashed and dot-dashed lines, respectively.

### 3 COMPARISON WITH OBSERVATIONS

We compared the predicted and measured values of the line energy in the  $(E_{\alpha}, \lambda_{\text{Edd}})$  plane (Figure 2; only the calculations for a Schwarzschild BH are plotted, for simplicity). The Eddington ratios  $\lambda_{\text{Edd}}$  of the observed sample are taken from Zhou & Zhang (2010) and Zhou & Wang (2005), who studied a large sample of X-ray luminous AGNs. Using our theoretical curves, we can directly estimate the effective distance of the line-emitting region from the illuminating X-ray source, in the various sources. For instance, observational values falling on the dashed line corresponding to  $(r = 35r_{\text{g}}, h = 8r_{\text{g}})$  indicate a distance  $R = (r^2 + h^2)^{1/2} \approx 36 r_{\text{g}}$ . This distance determines a characteristic time lag between primary X-ray source and line emission. From the observed values of time lag and intrinsic line width, one can



**Figure 1.** Predicted line energies in the  $(E_{\alpha}, \lambda_{\text{Edd}})$  plane. The black lines are the results for a Schwarzschild BH; the blue lines are for a maximally spinning astrophysical BH. In each case, we repeated the calculation for six values of  $r$  (indicated as labels next to the Schwarzschild curves), and three values of  $h = 5r_{\text{g}}$ ,  $8r_{\text{g}}$ , and  $15r_{\text{g}}$ . For each  $r$  value, the three corresponding  $h$  curves are plotted as solid, dashed and dot-dashed lines, respectively.



**Figure 2.** Comparison of the observed Fe K $\alpha$  line energies with the predicted values. For simplicity, here we show only the  $(r, h)$  families of curves calculated for a Schwarzschild BH. The radial distances and the meaning of the solid, dashed and dot-dashed lines are the same as in Figure 1. The  $E_{\alpha}$  values observed in narrow-line Seyfert 1 galaxies (NLS1) are plotted as blue stars; those from broad-line Seyfert 1 galaxies (BLS1) are magenta triangles; those from quasars are orange squares. Multiple line energies are plotted for most galaxies. See Table 1 for details of the observed values.

estimate the BH mass and spin, with the iron line reverberation method (Reynolds et al. 1999; Liu et al. 2010). In the rest of this section, we compare the line emission distances inferred from the  $(E_{\alpha}, \lambda_{\text{Edd}})$  plane with those estimated in the published literature, for a sample of Seyfert galaxies.

**NGC 7314:** simultaneous observations of the NLS1 NGC 7314 with *Chandra* and *RXTE* have revealed variability in the spectral features on a timescale  $< 12.5$  ks (Yaqoob et al. 2003), corresponding to a light-crossing distance of  $\approx 500r_{\text{g}}$  and a Keplerian radius of  $\approx 18.5r_{\text{g}}$  for a BH mass of  $10^{6.70} M_{\odot}$  (Zhou & Wang 2005). This is in excellent agreement with the Fe xxv emission region ( $\approx 20r_{\text{g}}$ )

estimated for this object from our line energy curves (Figure 2).

**Mrk 766:** the X-ray spectra of the NLS1 Mrk 766 show a broad emission line at  $\approx 6.7$  keV (Pounds et al. 2003). From our plots in Figure 2, we infer that the Fe XXV emission region is located at  $35r_g \lesssim r \lesssim 50r_g$  from the central BH. In addition, Turner et al. (2004) found a transient narrow line at  $\approx 5.6$  keV and interpreted it as evidence for blob ejection of neutral or low-ionized material. If so, the rest-frame line energy is  $\approx 6.4$  keV, and the line emission region may be located at  $50r_g \lesssim r \lesssim 100r_g$ , corresponding to a distance of  $\sim 10^{14}$  cm for a BH mass of  $10^{6.6} M_\odot$  (Zhou & Wang 2005), in broad agreement with the results of Turner et al. (2004).

**1H0707–495:** the spectrum of this NLS1 galaxy shows a sharp drop at energies  $\approx 7\text{--}7.5$  keV (Boller et al. 2002; Gallo et al. 2004b). A partial covering model was introduced to reduce the need for an extreme iron overabundance (Tanaka et al. 2004). However, an alternative possibility is that the X-ray spectrum is dominated by ionized reflection rather than absorption. In this scenario, it was argued (Fabian et al. 2004) that the two *XMM-Newton* observations support the light bending model of Miniutti & Fabian (2004). Fabian et al. (2009) also measured a time lag of about 30s between the soft energy band (0.3–1 keV) and the medium energy band (1–4 keV). Combining this short time lag with the measured width of the broad iron L emission, they suggested that the X-ray reverberation comes from matter very close to the event horizon of a rapidly spinning BH. However, considering a larger energy range (0.3–7.5 keV), Miller et al. (2010) argued instead that the observed time delays extend up to about 1800s in the hard band; this is consistent with reverberation caused by scattering of X-rays passing through much more distant absorbing material. For our adopted mass of  $10^{6.37} M_\odot$  (Zhou & Wang 2005),  $\lambda_{\text{Edd}} \sim 1$ . This suggests that 1H0707–495 may have a highly-ionized disk within  $\approx 50r_g$  for a Schwarzschild BH, or within  $\approx 20r_g$  for a rapidly spinning BH. In our scenario, those characteristic distances may be the origin of the observed iron K $\alpha$  lines at rest-frame energies  $\approx 6.5\text{--}6.7$  keV (Fabian et al. 2009; Zoghbi et al. 2010).

**NGC 3516:** simultaneous *Chandra* and *XMM-Newton* observations showed (Turner et al. 2002) two pairs of weak emission features, including a component at  $\approx 6.9$  keV, symmetrically located around a strong, narrow 6.4 keV line. This structure was interpreted (Turner et al. 2002) as evidence for relativistic broadening of disk lines from three different radii. In our model, we find that for  $\lambda_{\text{Edd}} \sim 0.01$  (Figure 2) even the innermost region of the accretion disk must remain neutral. Thus, if the observed 6.5 keV and 6.9 keV lines are emitted from the disk, they must be blue-shifted peaks of a 6.4 keV line, rather than being emitted by ionized iron. This supports the interpretation of Turner et al. (2002).

**Mrk 841:** we infer that the observed 6.4 keV line is emitted from a region  $\approx 50r_g$  from the central Schwarzschild BH (or closer, for a Kerr BH). This corresponds to a time lag of 20 ks for a BH mass of  $10^{7.90} M_\odot$  (Zhou & Wang 2005), in good agreement with the variability timescale  $< 36$  ks found in two *XMM-Newton* observations (Petrucci et al. 2002; Longinotti et al. 2004).

## 4 DISCUSSION AND CONCLUSIONS

Iron at the surface of an accretion disk is significantly ionized when the Eddington ratio  $\lambda_{\text{Edd}}$  is larger than a critical value. Assuming a standard viscosity parameter  $\alpha \sim 0.1$ , the critical value above which iron in the innermost part of the disk becomes ionized is  $\lambda_{\text{Edd}} \sim 0.1$  for a Schwarzschild BH, and  $\lambda_{\text{Edd}} \sim 0.3$  for a maximally-rotating astrophysical BH. We studied the radial ionization structure of an X-ray illuminated accretion disk, and calculated the energy (increasing with the ionization parameter) of the iron K $\alpha$  lines emitted from the disk. We plotted those energies as family of curves in the  $(E_\alpha, \lambda_{\text{Edd}})$  plane, parameterized in terms of radial distance of the emitters and height of the illuminating X-ray source above the disk plane (lamppost model), for a non-rotating and a maximally-rotating BH. We compared our model with the observed K $\alpha$  line energies from a sample of AGNs.

A substantial fraction of AGNs show highly-ionized iron K $\alpha$  emission. The origin of the ionized emission is still debated. Our results suggest that it may come from two different sources: the accretion disk (for  $\lambda_{\text{Edd}} \gtrsim 0.1$ ) or the photoionized material in the outflow (for  $\lambda_{\text{Edd}} \lesssim 0.1$ ). Our model presented here is based on simple assumptions, such as constant density without vertical stratification (Matt et al. 1993), but our main goal is to illustrate an important physical effect, which is unlikely to depend substantially on the details of the disk structure.

The critical  $\lambda_{\text{Edd}}$  depends on  $\alpha$ , which parameterizes our ignorance of detailed accretion physics (Ji et al. 2006; Miller et al. 2006). Despite forty years of observational, experimental and theoretical studies since Shakura & Sunyaev (1973), we are still unable to determine the disk viscosity accurately. The theoretical dependence of the observed iron K $\alpha$  line energy on  $\alpha$  suggests that we can reverse the argument: if we have independent measurements of a BH mass, spin and luminosity, we can estimate  $\alpha$  using the ionization curves in the  $(E_\alpha, \lambda_{\text{Edd}})$  plane, by combining the information on centroid energy and rapid variability timescale. It is plausible that  $\alpha \sim 0.1$  is in agreement of iron line observations of a few AGNs.

Iron near the disk surface cannot be ionized at low accretion rates and low Eddington ratios. There is a forbidden region in the  $(E_\alpha, \lambda_{\text{Edd}})$  plane, below which ionized K $\alpha$  line emission cannot come from an irradiated disk. Observationally, several low-luminosity AGNs in that region show K $\alpha$  emission features at 6.5–6.9 keV. We argued that such features are either coming from a highly-ionized outflow, or are blue-shifted components from fast-moving neutral matter. Alternatively, the intermediate energy line (6.5–6.7 keV) seen in NGC 3516, NGC 7213 and Fairall 9 may come from an evaporating/condensating region, as predicted by the disk transition model at  $\lambda_{\text{Edd}} \sim 0.01\text{--}0.02$  (Róžańska & Czerny 2000; Liu & Taam 2009; Qiao & Liu 2009).

Finally, we emphasize that the current observations do not yet allow us to put robust constraints on the origin of the highly-ionized iron K $\alpha$  lines. The line parameters derived from X-ray spectral fitting are strongly model-dependent, and have large uncertainties. Future observations with the next generation of X-ray space telescopes (such as the proposed *GRAVITAS* mission) will resolve the profile and con-

**Table 1.** Observed rest-frame central energies of the iron  $K\alpha$  lines in our sample of galaxies. Col.(1): common name of the object; Col.(2): redshift, from the NASA/IPAC Extragalactic Database (NED); Col.(3): source of the X-ray data; Col.(4-6): centroid energies ( $f$  fixed); Col.(7): Eddington ratio, from Zhou & Zhang (2010) and Zhou & Wang (2005); Col.(8): references for the X-ray spectra: (1) Patrick et al. (2010); (2) Gallo et al. (2004a); (3) Takahashi et al. (2010); (4) Schmoll et al. (2009); (5) Bianchi et al. (2004); (6) Bianchi et al. (2005); (7) Fabian et al. (2009); (8) Turner et al. (2002); (9) Reeves et al. (2004); (10) Pounds et al. (2003); (11) Reeves et al. (2001); (12) Reynolds et al. (2004); (13) Longinotti et al. (2003); (14) McKernan & Yaqoob (2004); (15) Matt et al. (2001); (16) Pounds et al. (2001); (17) Bianchi et al. (2003); (18) Yaqoob et al. (2003); (19) Petrucci et al. (2002).

Source	Redshift	Mission	$E_{\alpha 1}$ (keV)	$E_{\alpha 2}$ (keV)	$E_{\alpha 3}$ (keV)	$\log(\lambda_{\text{Edd}})$	Ref.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Mrk 335	0.0258	<i>Suzaku</i>	$6.27^{+0.13}_{-0.17}$	$6.69^{+0.06}_{-0.05}$	$6.98^{+0.06}_{-0.14}$	0.05	1
I Zw 1	0.0589	<i>XMM-Newton</i>	$6.4^f$	$6.84^{+0.09}_{-0.11}$	...	0.12	2
Ton S180	0.0620	<i>Suzaku</i>	...	$6.7^{+0.1}_{-0.2}$	...	0.29	3
Fairall 9	0.0470	<i>Suzaku</i>	$6.16 \pm 0.2$	$6.74^{+0.04}_{-0.04}$	$6.98 \pm 0.02$	-1.72	1,4
ESO 198-G24	0.0455	<i>Chandra, XMM-Newton</i>	$6.38 \pm 0.06$	...	$6.97^f$	-1.36	5,6
Ark 120	0.0327	<i>Suzaku</i>	$6.36^{+0.08}_{-0.09}$	...	$6.96 \pm 0.04$	-0.99	1
1H 0707-495	0.0406	<i>XMM-Newton</i>	...	$6.5 - 6.7$	...	-0.04	7
NGC 3516	0.0089	<i>Chandra, XMM-Newton</i>	$6.41 \pm 0.01$	$6.53 \pm 0.04$	$6.84 - 6.97$	-1.89	8
NGC 3783	0.0097	<i>XMM-Newton</i>	$6.39 \pm 0.01$	...	$7.00 \pm 0.02$	-1.36	9
Mrk 766	0.0129	<i>XMM-Newton</i>	$6.40^f$	$6.67 \pm 0.08$	...	-0.26	10
Mrk 205	0.0708	<i>XMM-Newton</i>	$6.39 \pm 0.03$	$6.74 \pm 0.12$	...	-0.57	11
NGC 4593	0.0090	<i>XMM-Newton</i>	$6.39 \pm 0.01$	...	$6.95 \pm 0.05$	-0.71	12
IRAS 13349+2438	0.1076	<i>XMM-Newton</i>	$6.0^{+0.3}_{-0.2}$	...	$7.0 \pm 0.1$	-0.58	13
IC 4329A	0.0161	<i>Chandra</i>	$6.301^{+0.076}_{-0.073}$	...	$6.906^{+0.028}_{-0.037}$	-0.83	14
NGC 5506	0.0062	<i>XMM-Newton</i>	$6.41 \pm 0.03$	$6.75^{+0.10}_{-0.15}$	...	-0.38	15
Mrk 509	0.0344	<i>XMM-Newton</i>	$6.36 \pm 0.03$	...	$6.91 \pm 0.09$	-1.10	16
NGC 7213	0.0058	<i>XMM-Newton</i>	$6.39 \pm 0.01$	$6.65^{+0.04}_{-0.06}$	$6.94^{+0.05}_{-0.10}$	-1.79	17
NGC 7314	0.0048	<i>Chandra</i>	$6.405^{+0.016}_{-0.017}$	$6.607^{+0.011}_{-0.017}$	$6.931^{+0.018}_{-0.011}$	-0.65	18
MCG-02-58-22	0.0469	<i>XMM-Newton</i>	$6.29^{+0.26}_{-0.06}$	...	$6.97^f$	-1.78	5,6
Mrk 841	0.0364	<i>XMM-Newton</i>	$6.41^{+0.05}_{-0.06}$	...	...	-0.36	19

strain the origin of those lines, and test X-ray reverberation mapping in a large sample of AGNs.

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